Blood oxygenation level-dependent (BOLD) based imaging in skeletal muscle at 3 and 7T

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Introduction

In addition to studies of neural function the blood oxygenation level dependent (BOLD) response also has been used to assess heart, kidney, lung, and skeletal muscle function (1). The biophysical basis of the BOLD contrast originates from both intravascular (hemoglobin saturation, hemoglobin content) and extravascular (hemoglobin saturation, hemoglobin content, microvascular density, and the orientation of the vessels relative to the main magnetic field (B_0)) sources (2). In skeletal muscle the intravascular BOLD dominates due to the relatively large dynamic range in blood flow, hemoglobin saturation, and hemoglobin content seen during the commonly used protocols and the low angle of incidence of the vessels with respect to B_0 (3,4). At ultra high-fields > 3T where the blood T_2* is very short (~ 15 ms or less) muscle BOLD contrast may be predominately extravascular in nature and therefore would provide information on the structural aspects of the vascular anatomy. This information may be of particular importance in chronic disease such as metabolic syndrome and diabetes where pathological changes occur in the vascular anatomy including reduced microvascular density and shorter and narrower capillaries (5). Therefore the purpose of this study was to determine the feasibility of muscle BOLD imaging at 7T by comparing the changes in T_2* of skeletal muscle at 3 and 7T in response to a brief period of tourniquet-induced ischemia.

Methods

Three male subjects, aged 29.3 ± 7.7 yrs, 176.9 ± 9.6 cm tall with a body mass of 83.4 ± 20.1 kg (mean ± SD), participated in the study. All subjects were free from physician diagnosed chronic disease. Subjects reported to the lab on three occasions. Visits were scheduled at the same time of day (± 1 hr) and each visit was separated by at least 1 but no more than 2 weeks. On the initial visit the subjects' height, weight, and blood pressure were recorded and the subject was familiarized with the reactive hyperemia (RH) protocol. *RH Protocol:* A thigh-specific tourniquet was placed proximal to the knee joint and rapidly inflated (~ 1 sec) to a pressure of 250 mmHg and maintained for 5 mins. Experimental days 2 and 3 included visits to either the 3 or 7T imaging suite. *General MRI procedures:* Subjects were positioned supine in the scanner with the largest portion of the left calf centered in an extremity coil. Care was taken to standardized patient positioning across visits and the same RH protocol was used for all visits. *3T procedures.* All images were acquired using a Philips Intera Achieva, whole-body scanner and an 8-channel receive only knee coil. High-resolution anatomical images (turbo spin-echo, FOV = 200 mm^2, 11 slices, 5 mm slice thickness) centered at mid-calf were acquired for planning purposes. Functional images (multi-shot, multi-echo turbo field echo, echo-planar images (TFE-EPI) *TR* 1000 ms, 15 echos, min *TE* 4.4, echo spacing 6.1 ms, acq. matrix of 64 x 64 and reconstructed to 128 x 128) were acquired continuously for 14 mins including 2 mins of baseline, 5 mins of ischemia and 7 mins of reactive hyperemia. *7T procedures:* Scanning was performed on a Philips 7T scanner using a transmit/receive partial volume extremity coil. High-resolution anatomical scans were acquired for localization. The functional images were acquired at the same anatomical location as in the 3T study and the imaging sequence was nearly identical (multi-shot, multi-echo turbo field echo, echo-planar images (TFE-EPI) *TR* 1000 ms, 15 echos, min *TE* 4.3, echo spacing 6.1 ms) *Data Analysis:* Images were analyzed in Matlab (MathWorks®, Cambridge, MA) using custom written code. T_2* values were calculated from exponential fitting of the T_2* decay curve assuming a mono-exponential decay.

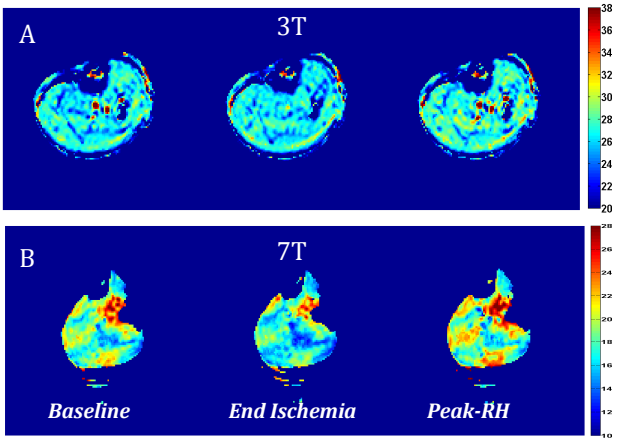

Figure 1: TFE-EPI images of a human leg at 3 (A) and 7T (B) during the RH protocol. From left to right: resting, end-ischemia, and peak-RH.

Results

Figure 1 displays images acquired at 3 (A) and 7T (B) at rest, end-ischemia, and the peak-RH. Changes in T_2* across the muscles at the end of ischemia is apparent in the 7T image and more dramatically in both images at peak RH. The time course of changes in T_2* during the RH protocol for one subject is presented in figure 2. In both cases (3T, top red tracing and 7T, bottom blue tracing) there is a large drop in T_2* when the cuff is initially released at 420 secs into the protocol and this followed by a large increase in T_2* during the RH. For the 3 subjects the T_2* star of skeletal muscle (mean ± SE) at rest was 28.07 ± 0.34 ms and 16.51 ± 0.48 ms at 3 and 7T respectively. The end ischemia T_2* was 27.83 ± 0.28 ms and 15.5 ± 0.46 ms and the T_2* at peak-RH was 28.94 ± 0.29 ms and 17.07 ± 0.49 ms for 3 and 7T respectively. The uniformity of the image (figure 1) is considerably better at 3T however the relative change in T_2* from end-ischemia to peak RH was considerably larger at 7 vs. 3T (10.1 vs. 3.9%, respectively).

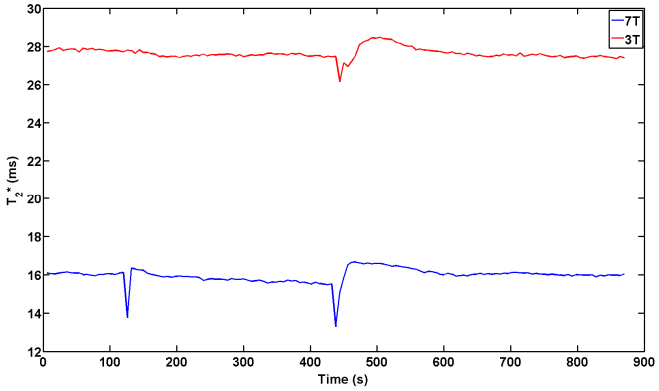

Figure 2: Time course of changes in T_2* during a RH protocol. The top tracing (red) shows the changes at 3T while the lower line (blue) are the T_2* changes in muscle at 7T. The T_2* of resting skeletal muscle at 7T is almost half that of the T_2* at 3T.

Conclusion

Our data suggest that BOLD based muscle functional imaging is feasible at ultra-high field strengths such as 7T. With improved coil design, B_1 insensitive pulses, and improved shimming routines the improved image quality should allow for a quantitative analysis of the biophysical analysis of the muscle BOLD at ultra-high fields.

References

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